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EXPLORING BROAD AREA QUANTUM CASCADE LASERS

Tim Newell, et. al.

1 October 2017

Technical Paper

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14. ABSTRACT

Quantum Cascade Lasers fabricated for multi-transverse mode operation have seldom been investigated. And yet they exhibit curious behavior such as the coherent locking of low order modes or apparently oscillating in a single but high-order transverse mode. As opposed to the commonly used semiconductor diode laser, quantum cascade lasers are unipolar devices creating photons from electron transitions in the conduction band. This changes their inherent time scales and also leads to a very low linewidth enhancement factor. Thus their intrinsic performance can be substantially different than their diode counterparts. In this talk we explore a 40-micron wide broad area laser with and without feedback from an external mirror. The interest is to see if feedback can alter the transverse modes, their time scales, and if this feedback leads to nonlinear oscillations and perhaps chaos.

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Quantum-well diode; Mid-IR; Brightness scaling; Broad area lasers

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Exploring Broad Area Quantum Cascade Lasers

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Abstract

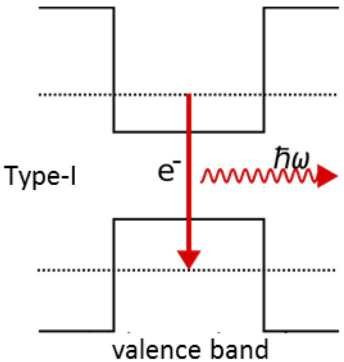
Quantum Cascade Lasers fabricated for multi-transverse mode operation have seldom been investigated. And yet they exhibit curious behavior such as the coherent locking of low order modes or apparently oscillating in a single but high-order transverse mode. As opposed to the commonly used semiconductor diode laser, quantum cascade lasers are unipolar devices creating photons from electron transitions in the conduction band. This changes their inherent time scales and also leads to a very low linewidth enhancement factor. Thus their intrinsic performance can be substantially different than their diode counterparts. In this talk we explore a 40-micron wide broad area laser with and without feedback from an external mirror. The interest is to see if feedback can alter the transverse modes, their time scales, and if this feedback leads to nonlinear oscillations and perhaps chaos.

Outline

Broad Area Quantum Cascade Lasers
Feedback Experiments
Beam Control
Temporal Dynamics
Mode Control Methods
Summary

III-V Semiconductor Lasers

Quantum Well Laser



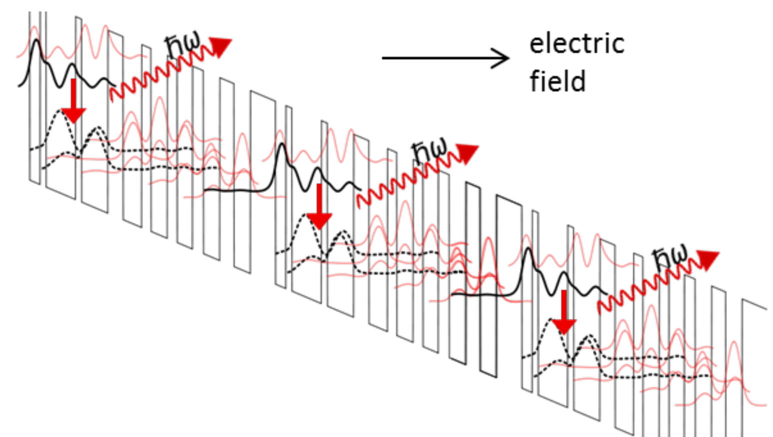
Electron – hole recombination

λ: ~200nm to 3720nm

Easy to grow:
9 to 12 alloy layers with
3- to 5-QWs in parallel

Electrical to optical efficiency can be over 70%.

Quantum Cascade Laser



Unipolar Electron transitions

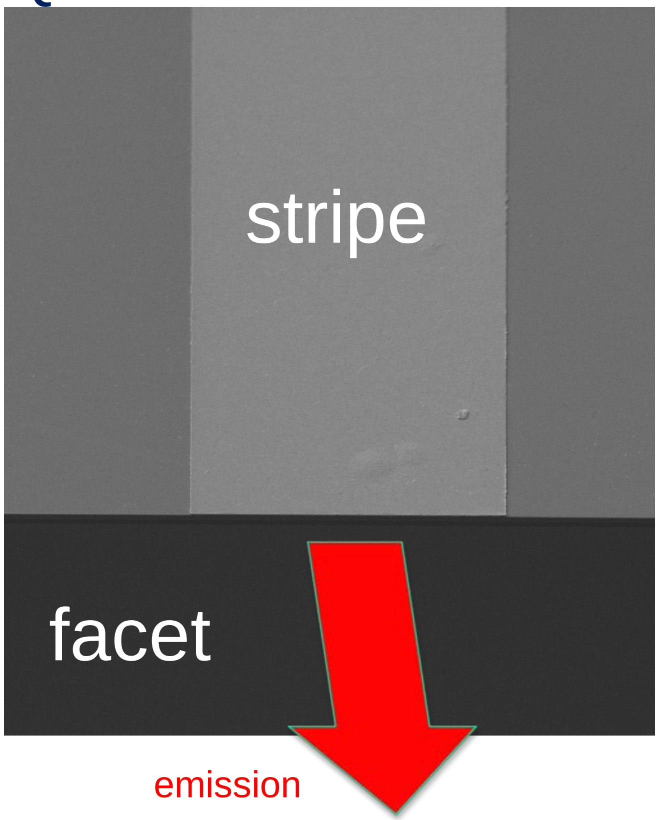
λ: ~3500nm to 30µm

Demanding growth:
25- to 35-stages in series and
~270 alloy layers

<10% efficiency is normal.
25% is the record

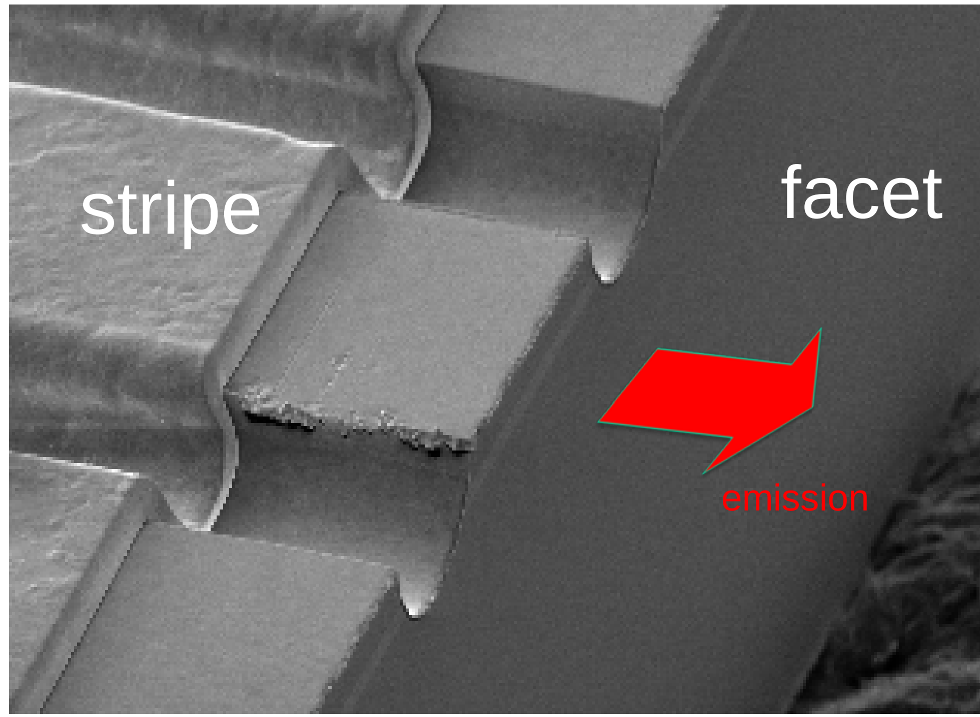
QW & QCL material processing

Quantum Well Laser



Minimal current spreading:
Laser cavity defined by the electrical contact.

Quantum Cascade Laser

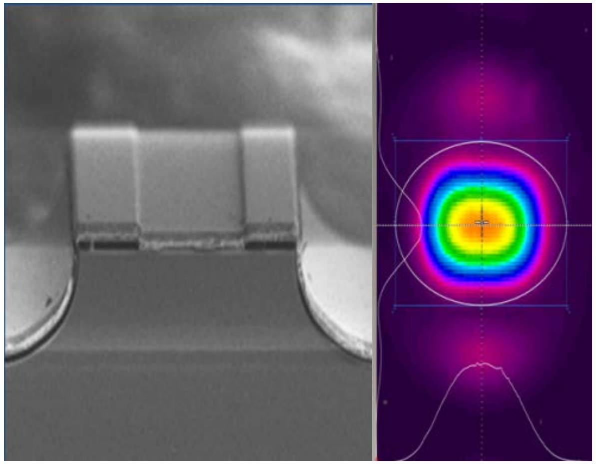


Strong current spreading:
Trenches etched deeper than the active region.

Single to Multi-Transverse Modes

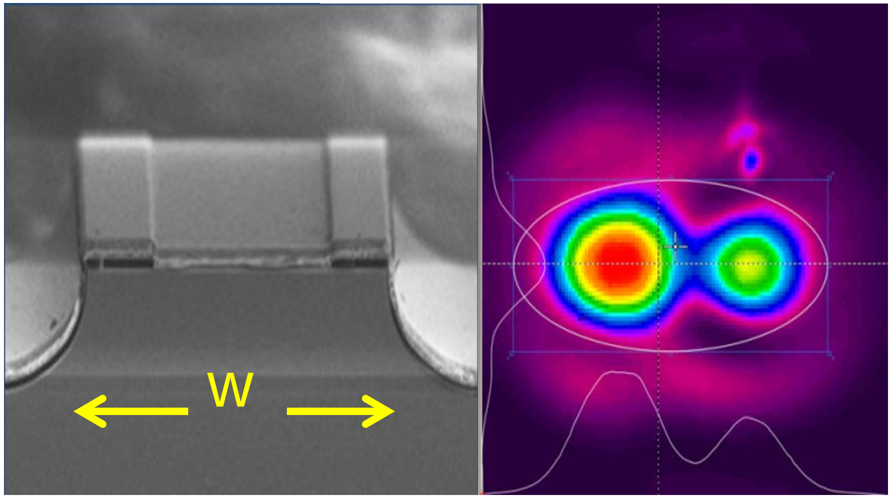
Narrow ridge <10μm

Stable fundamental mode



Widen the ridge > ~10μm

Higher order modes appear.

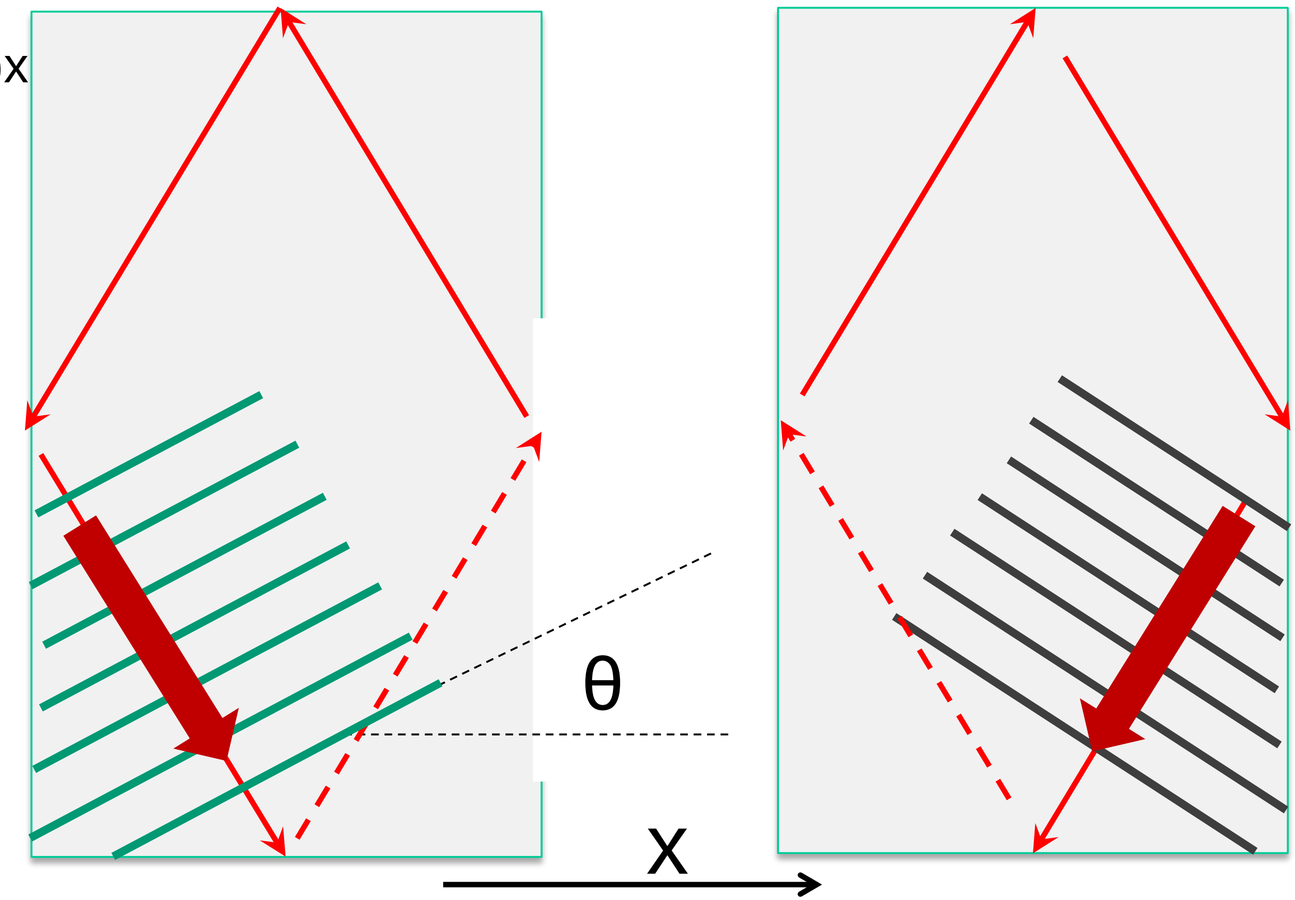


High-Order Transverse Modes

The modes can also be considered as two plane waves cycling through the rectangular "box" cavity.

$$E \sim e^{\pm i(2\pi n \sin\theta/\lambda)x}$$

n: refractive index
Θ: the angle measured within the cavity.

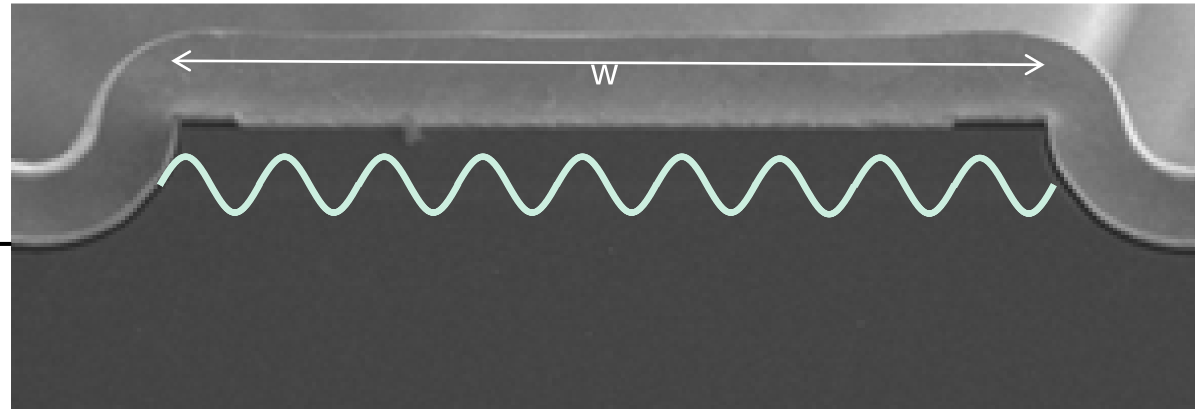


Transverse modes

Box resonator

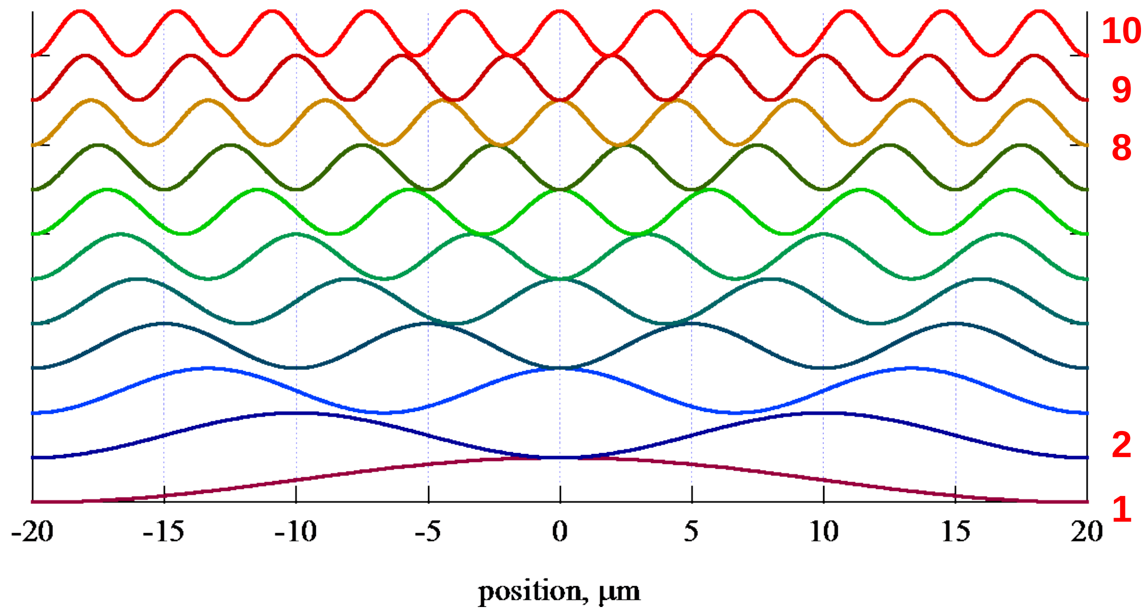
$$E_m = \begin{cases} odd: & \cos\left(M\pi x / w\right) \\ even: & \sin\left(M\pi x / w\right) \end{cases}$$

x



Expect the electric field to be an **incoherent** superposition of each mode

$$E = \sum_m E_m$$



2 Dimensional Geometry Model

Plane waves self-reproduce on each cycle.

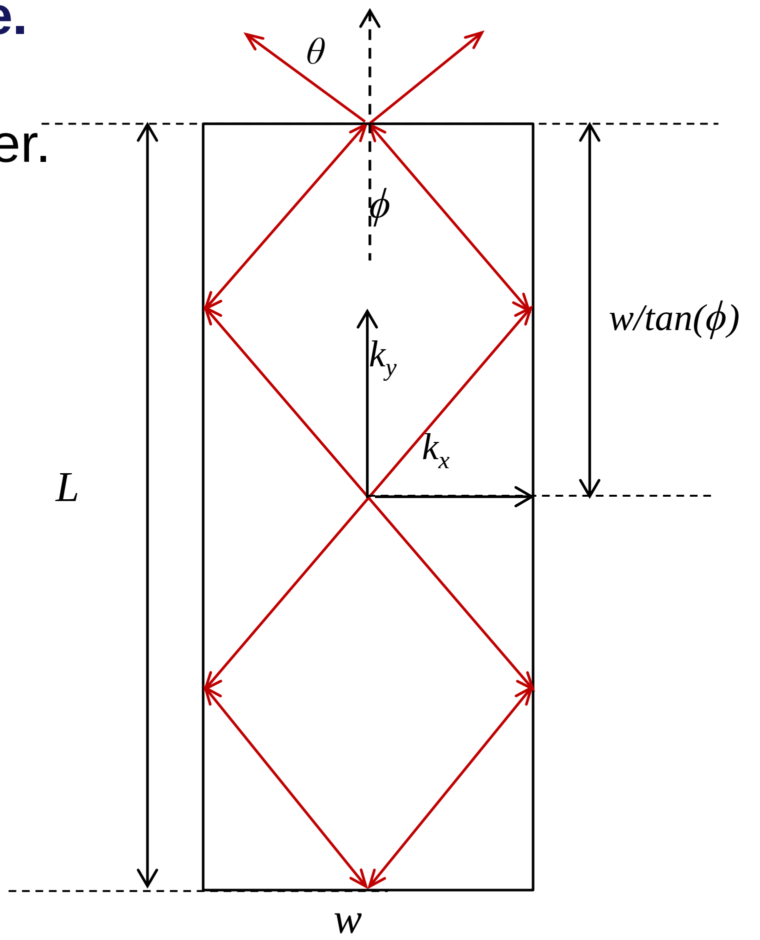
Define a lateral and longitudinal mode number.

M is the lateral mode number.

N is the diamond mode number.

Mode Number Equations:

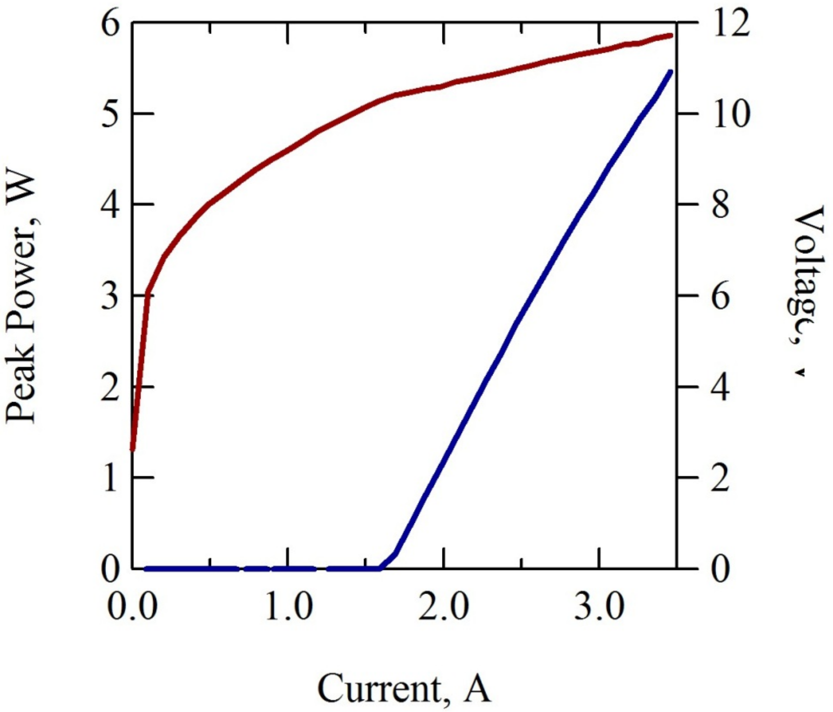
$$\underbrace{\sin\phi_M = \frac{\lambda M}{2nw} \quad \text{and} \quad \tan(\phi) = \frac{Nw}{L}}_{\textit{Restricts modes in cavity}}$$

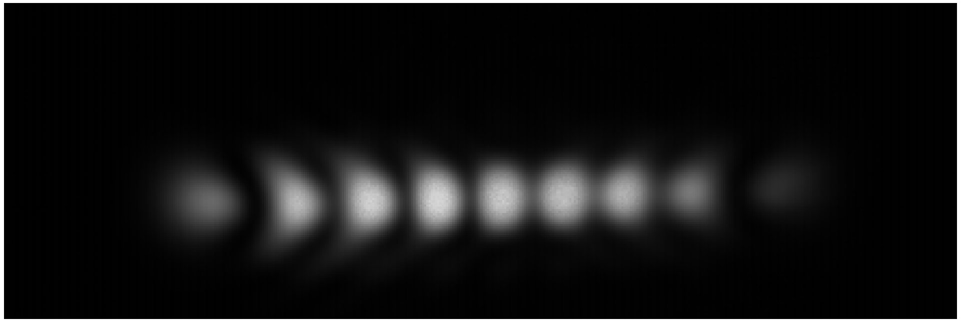


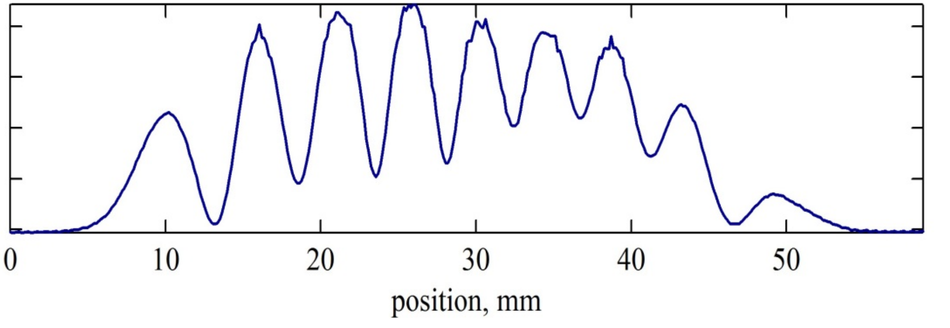
40µm BA-QCL

- **40µm stripe width.**
- Over 5W power.
- 500ns pulses / 0.5% duty cycle

- Near field image of the facets.
- Mode number, M = 9
- Intensity of antinodes isn't uniform.







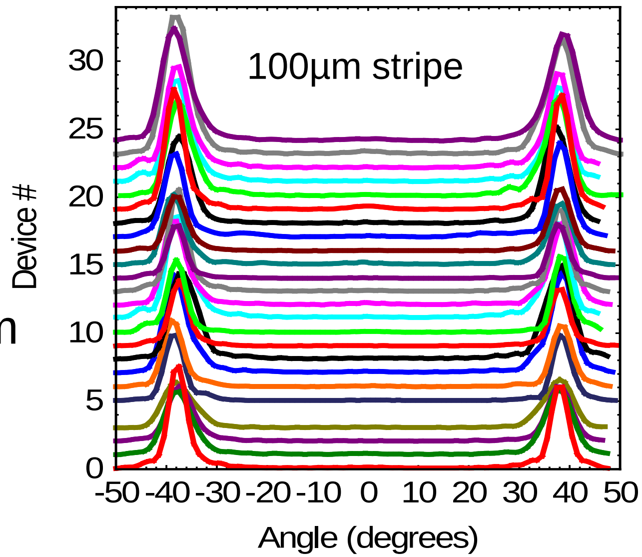
Line scan through image.

Far-Field BA-QCL beam

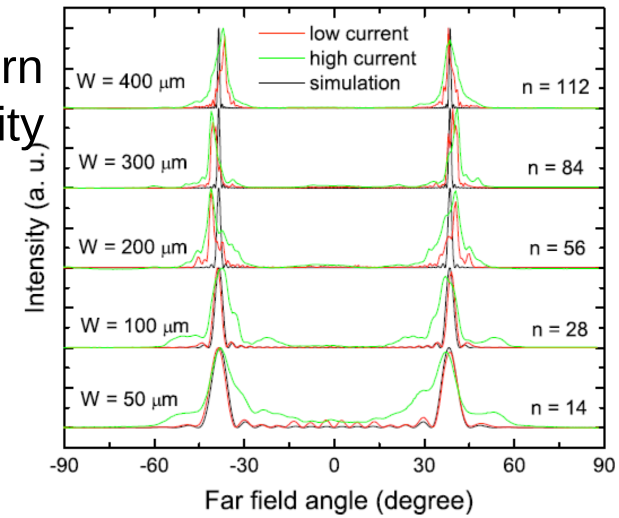
Single high order transverse mode exhibited in numerous QCLs

AFRL

100µm stripe QCL



Northwestern University



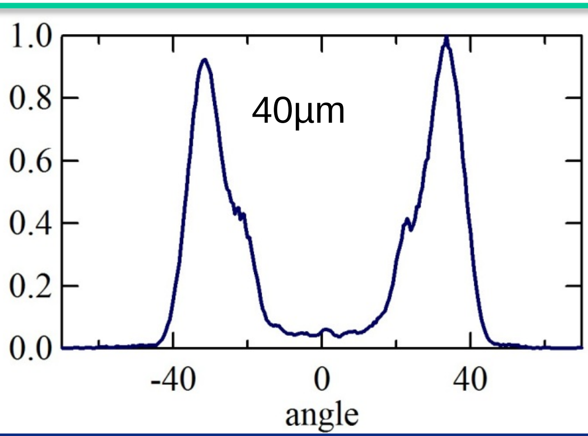
400µm

300µm

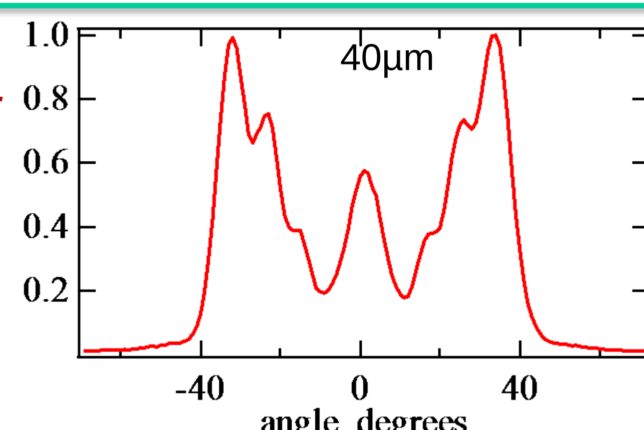
200µm

100µm

50µm



But not always simple:



Feedback into a QCL?

Feedback: Injecting the laser with a fraction of its emitted light.

- Feedback control of the transverse modes?
  - Can we create a new mode?
  - Can we steer the beam?
  - **Can we make a high brightness and high power QCL?**

- Feedback Dynamics?
  - What are the time scales?
  - Can we lock irregular pulsations?
  - Will feedback incite chaotic dynamics?

Lang-Kobayashi equations for external cavity feedback

Single longitudinal and transverse laser subject to external cavity feedback:

$$\frac{dE(s)}{ds} = (1 + i\alpha) NE(s) + \eta e^{i\varphi} E(s - \tau_c)$$

$$\varepsilon \frac{dN(s)}{ds} = J - N(s) - (2N(s) + 1)\left| E(s)^2 \right|$$

- E(s) is composed of transverse and longitudinal modes.
- α, the linewidth enhancement factor, **α ~0 in QCLs**
  - α = 3 to 5 in QW lasers
- $\varepsilon = \tau_s/\tau_p$ where τ_s = carrier lifetime = few ps.
  - ε~ 100 – 1000 in QW lasers & **ε ~ 1 – 10 in QCLs**

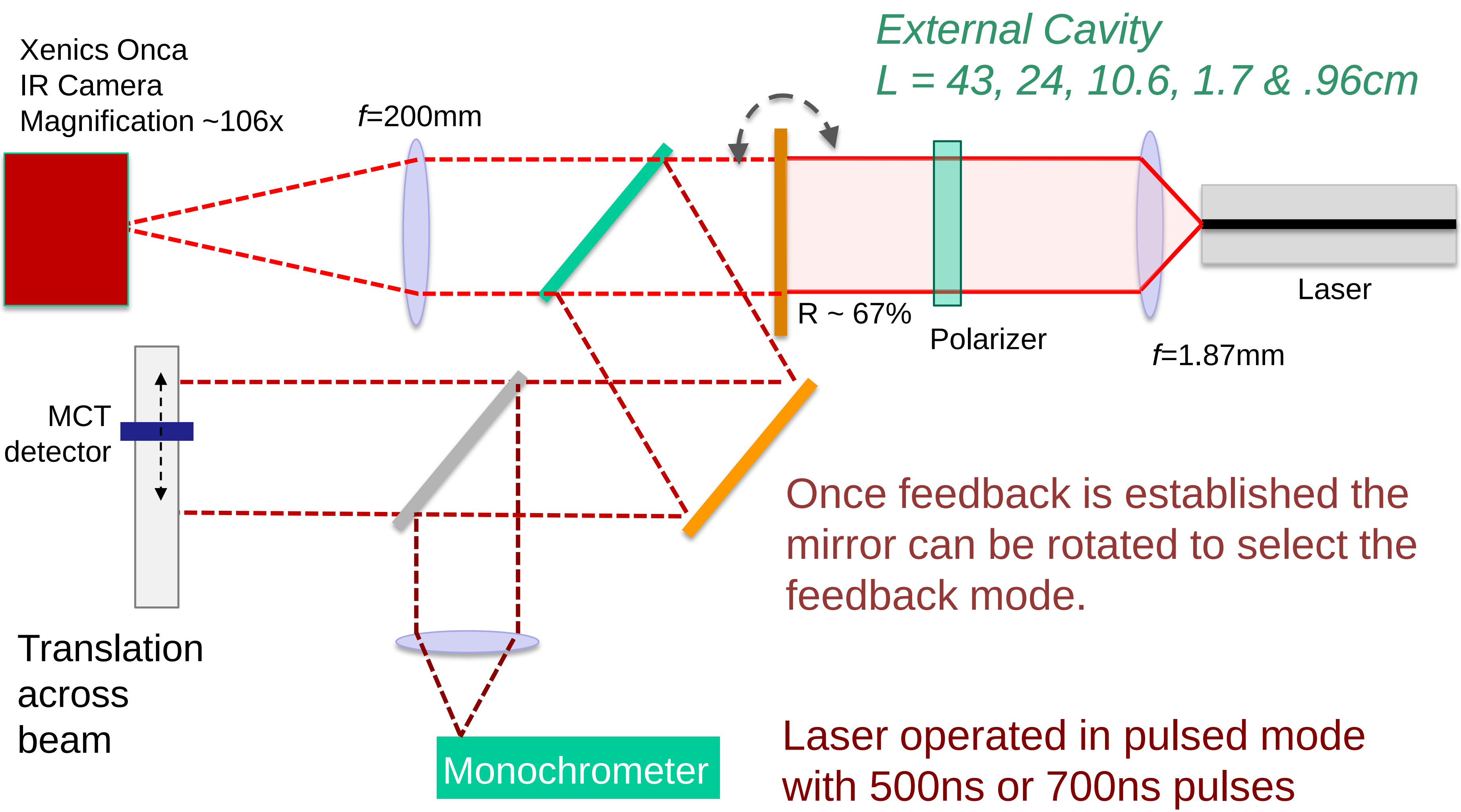
N is the dimensionless excess carrier number (inversion).
η is the feedback ratio. J is the excess pumping rate.
Feedback phase ϑ and round trip time, τ_c. $s = t/t_p$, dimensionless time.

Feedback Modeling and experiments

- Historical work
  - Almost always using diode lasers. Recent work with QCLs
  - Usually assumes **single** longitudinal mode
  - Laser cavity is **single** transverse mode
  - Modeling can be demanding but tractable

- Broad area feedback
  - **Multi**-longitudinal and transverse modes
  - Not yet modeled – quite complicated
  - No QCL studies and very limited diode experimental work

Experimental Arrangement



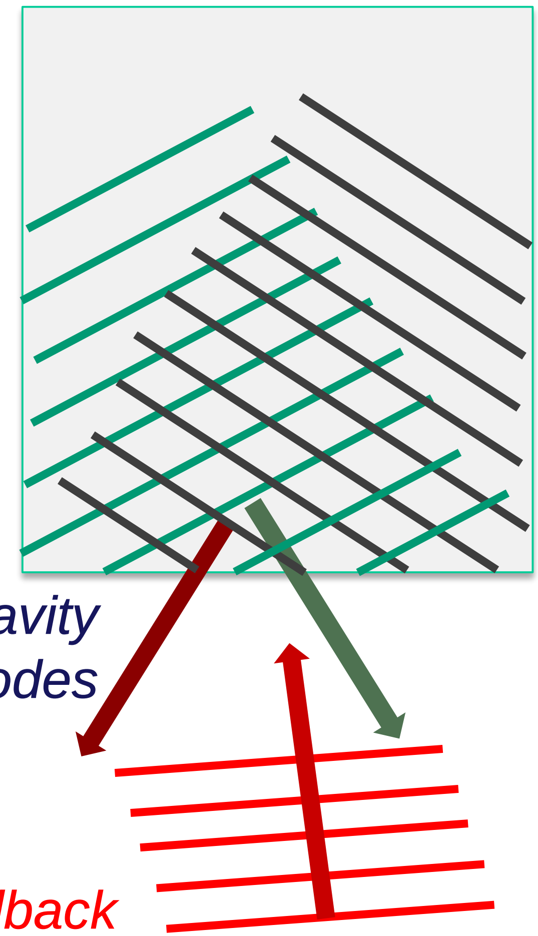
Once feedback is established the mirror can be rotated to select the feedback mode.

Laser operated in pulsed mode with 500ns or 700ns pulses

Beam Control

Simple visualization

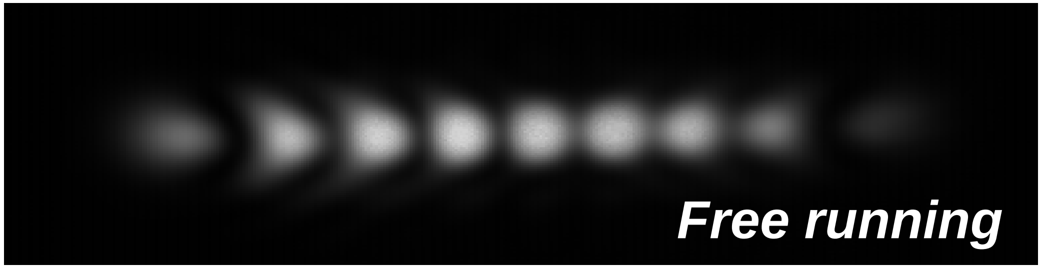
- Feedback incidence angle is adjustable
- External cavity length plays a role
- Feedback intensity can be set with polarizer
- Feedback can stabilize the existing mode or induce new modes.



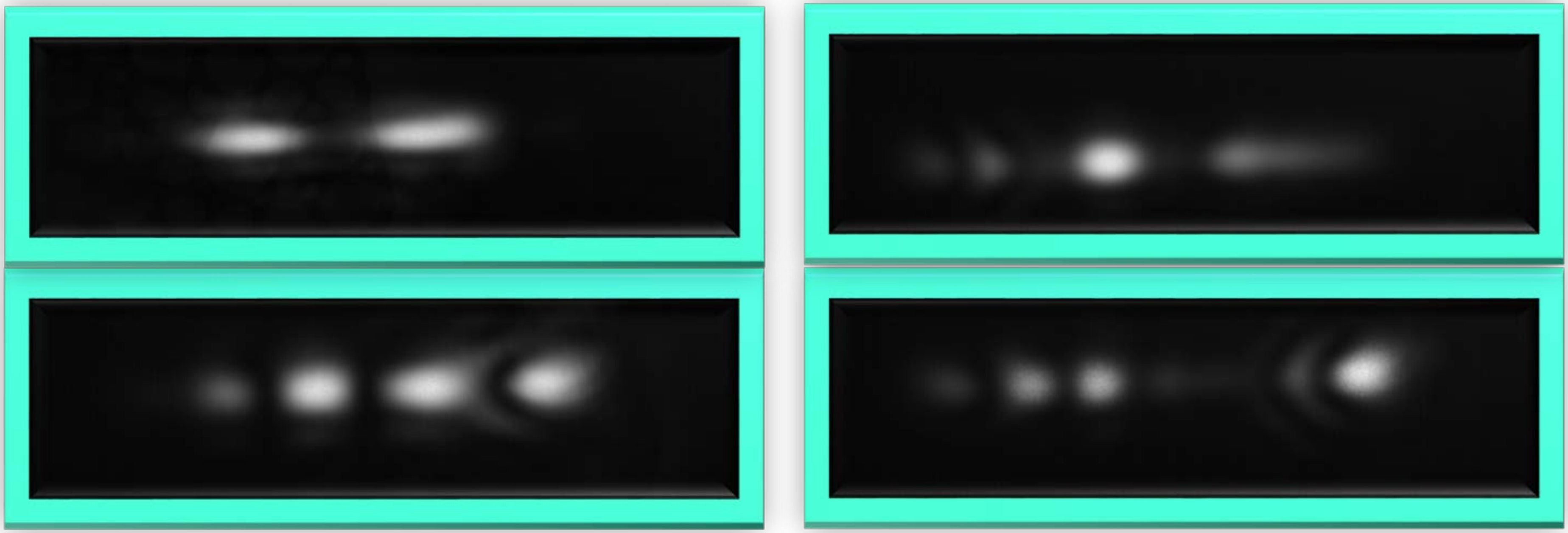
Cavity modes

Feedback mode

Success!

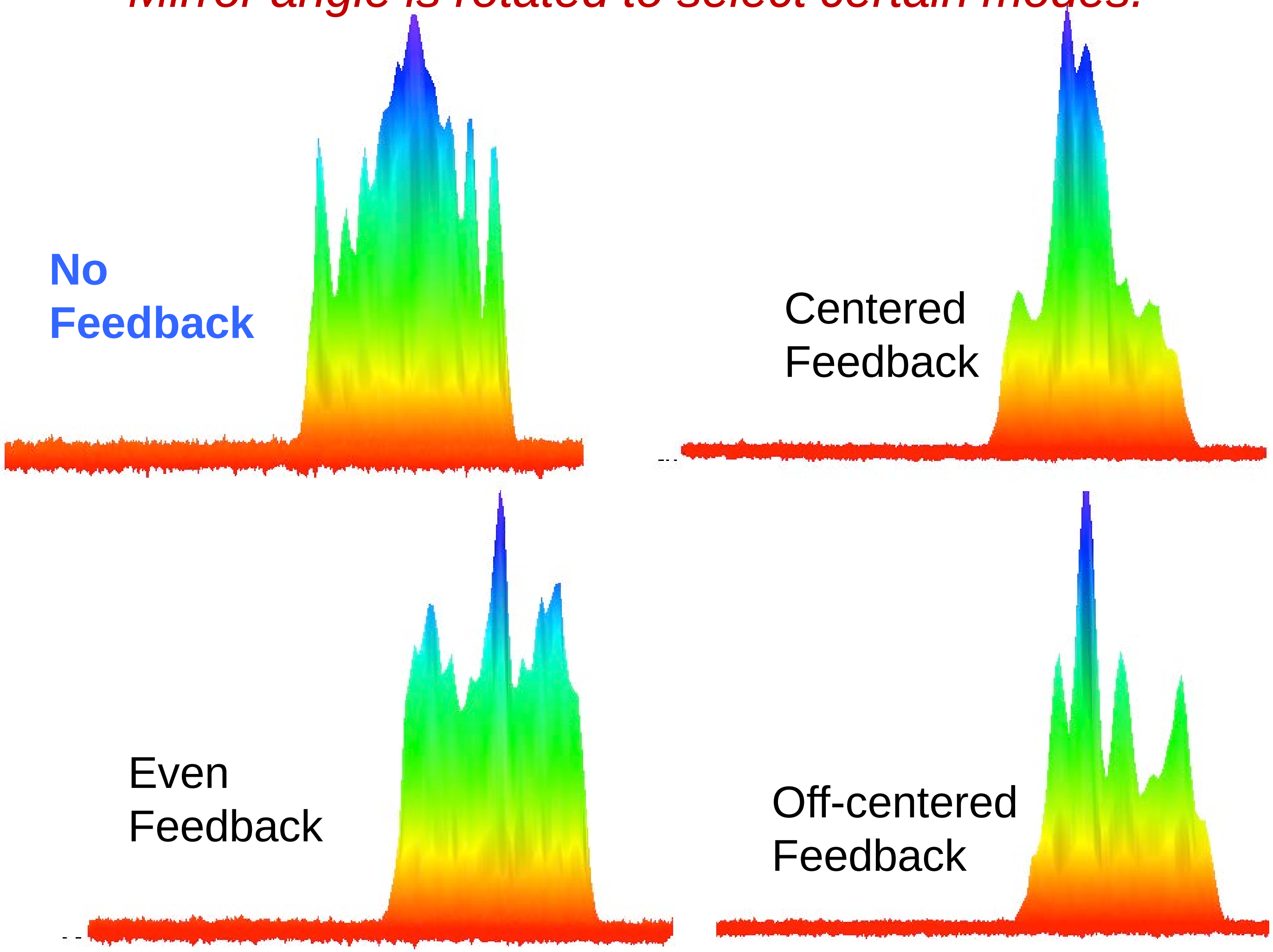


QCL facet near-field images show selection of different modes of operation based on the feedback incidence angle.



Line Scans from camera in a 24cm cavity

Mirror angle is rotated to select certain modes.

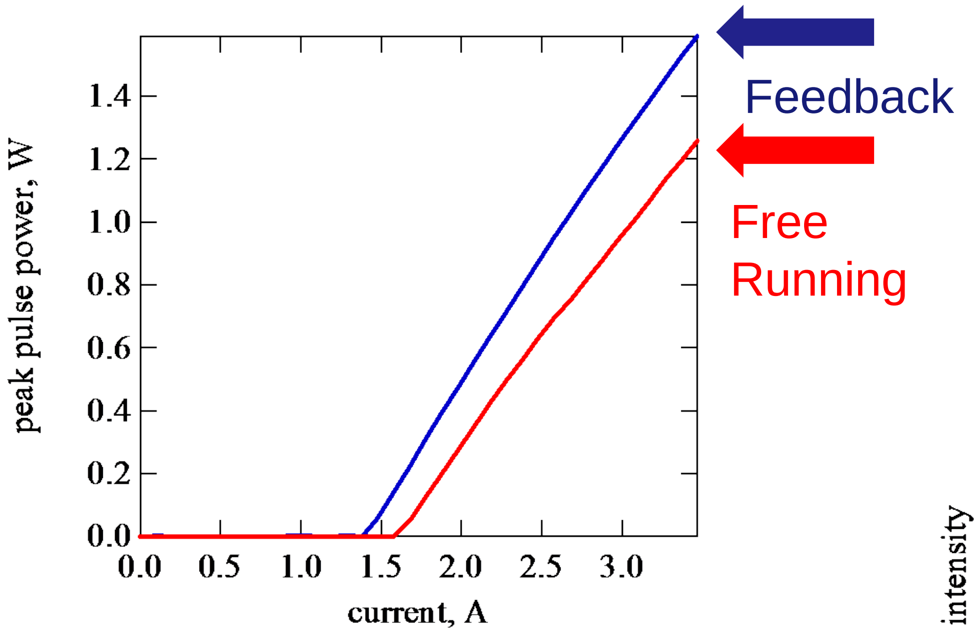


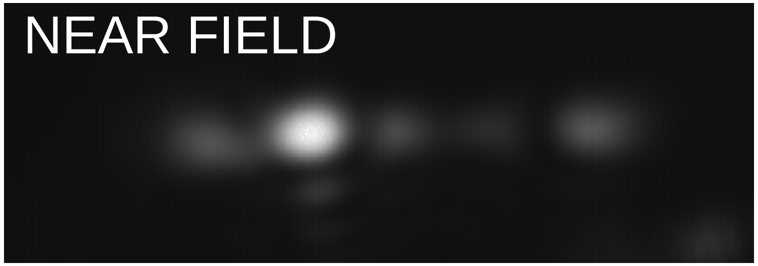
TELECOM ParisTech

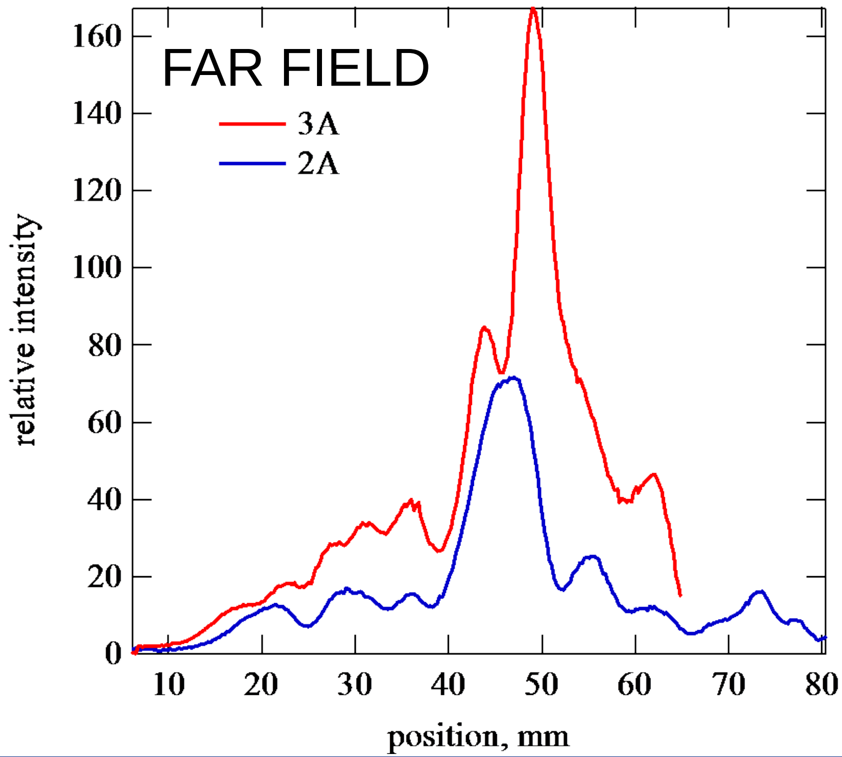
mirsense

Collaboration with Prof. Frederic Grillot , Louise Jumpertz and Matthieu Carras.

Maximizing Brightness



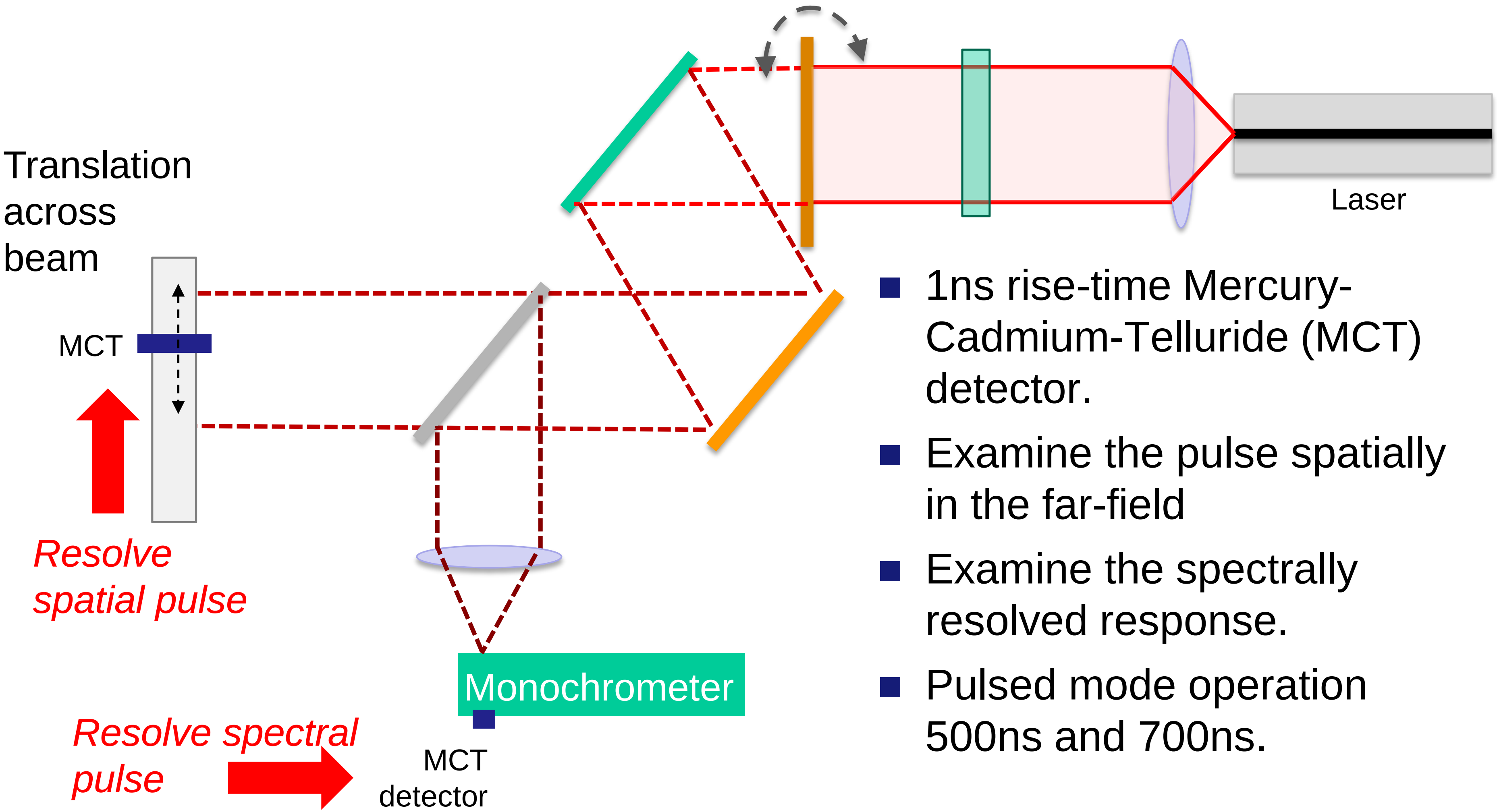




- 13% decrease in threshold.
- Increase in power.
- Far Field at 2m shows a strong single lobe.
- 10.6cm cavity length.

Temporal Dynamics

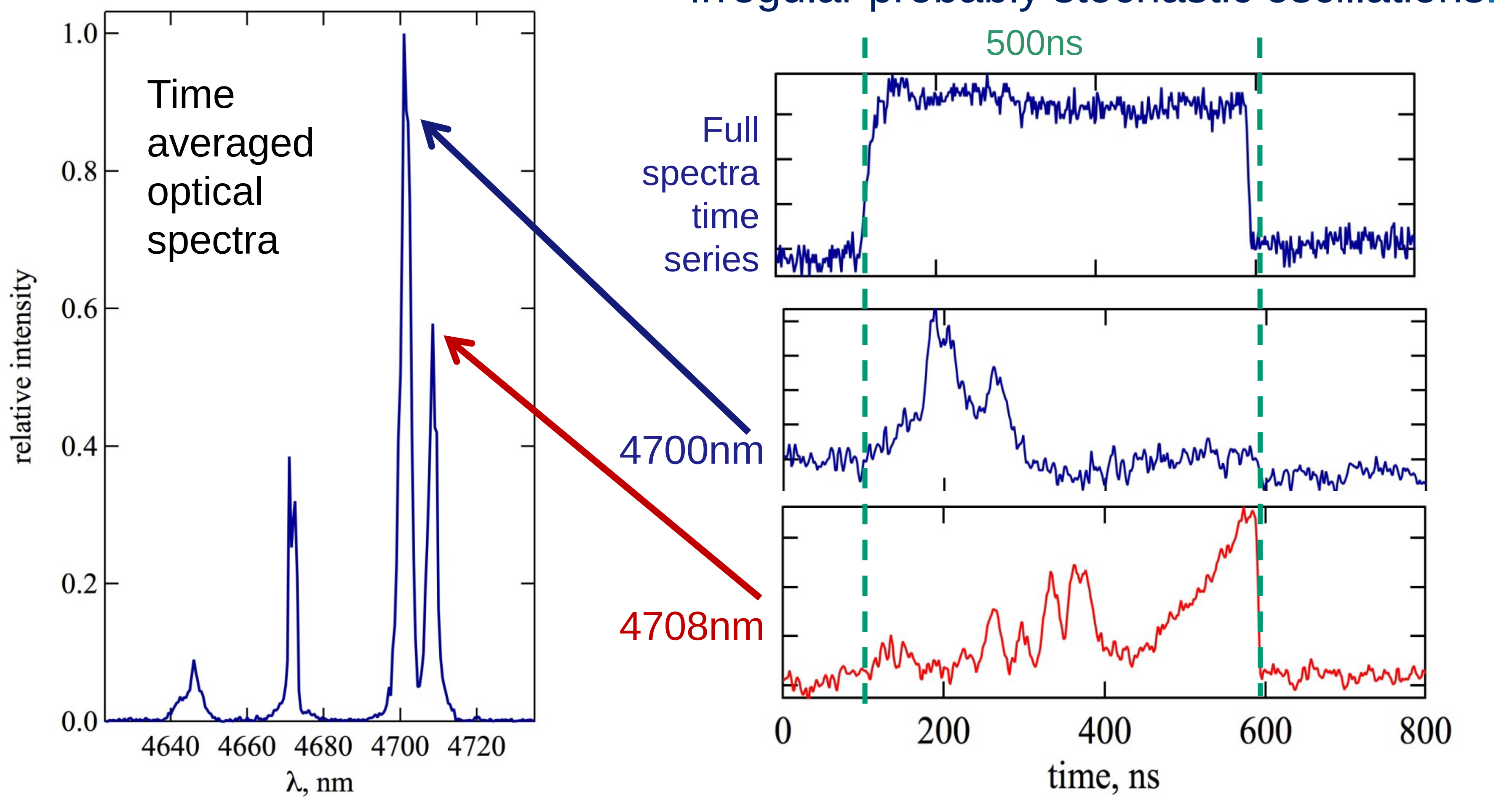
Experimental Arrangement



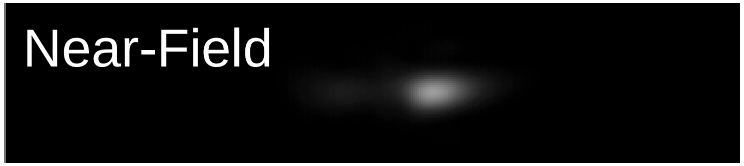
- 1ns rise-time Mercury-Cadmium-Telluride (MCT) detector.
- Examine the pulse spatially in the far-field
- Examine the spectrally resolved response.
- Pulsed mode operation 500ns and 700ns.

Free Running QCL – Spectra & Time Series

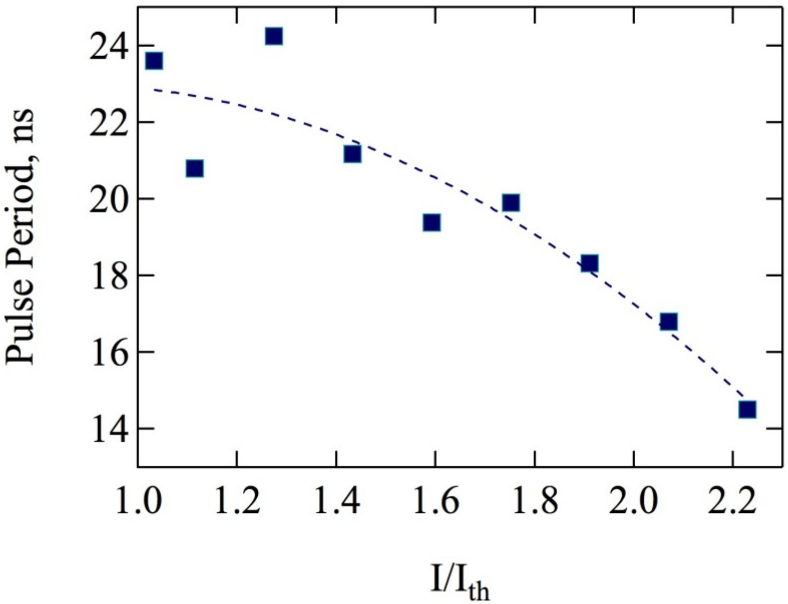
- Pulsed operation
- Longitudinal mode oscillations
- Irregular probably stochastic oscillations.

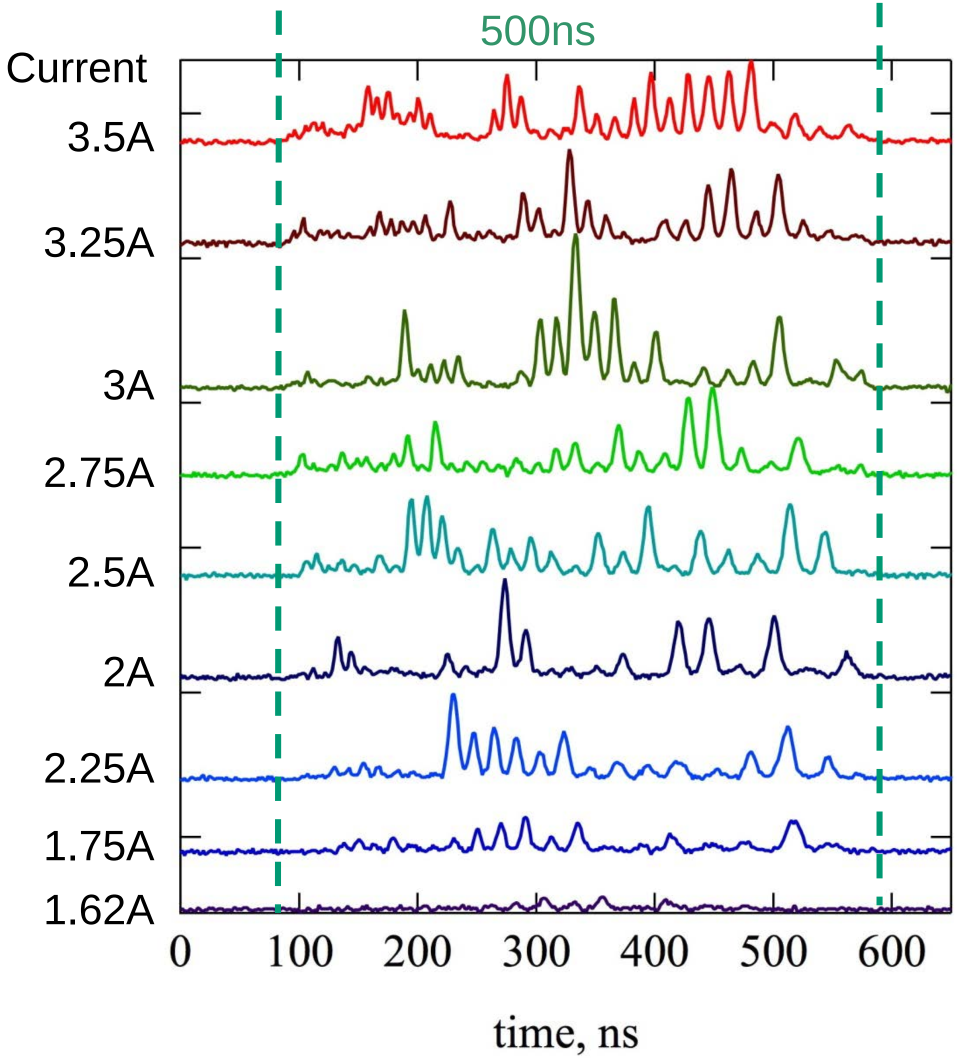


Longitudinal Mode Pulsations under feedback



- Wavelength fixed at 4758nm
- 8- to 10ns pulse widths
- 10.6mm cavity

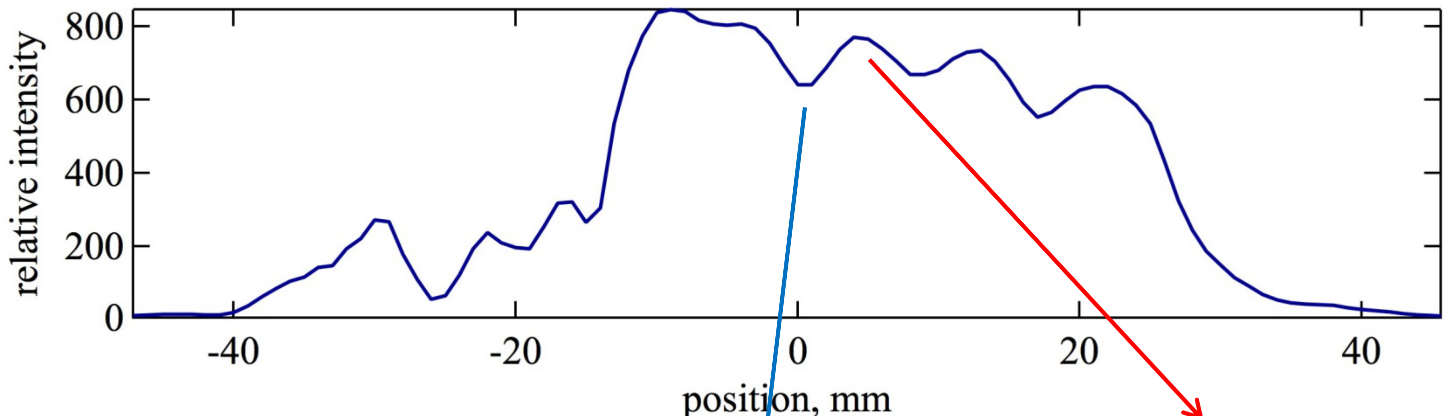




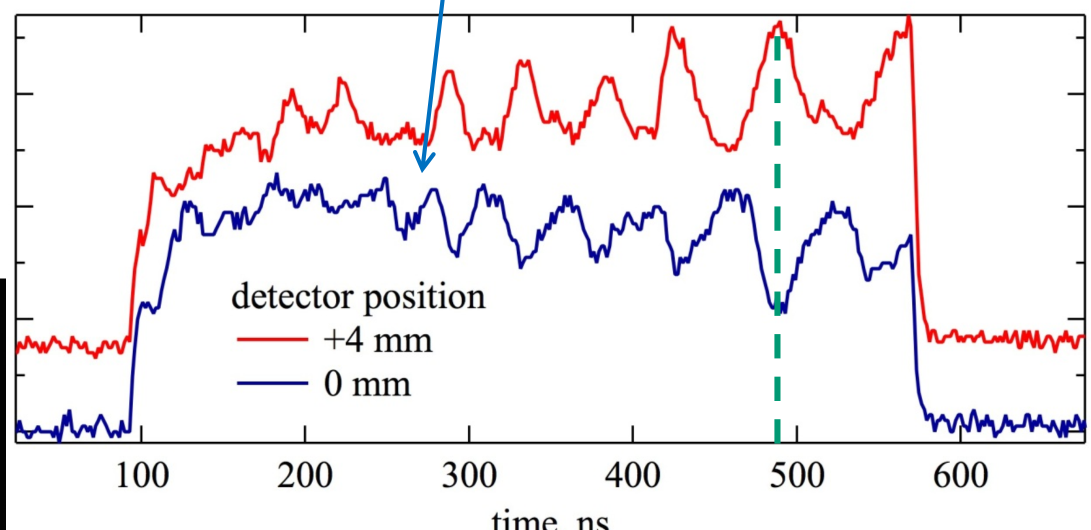
Transverse Mode Competition

Far-Field Spatial beam profile

Extract the time series at two locations.

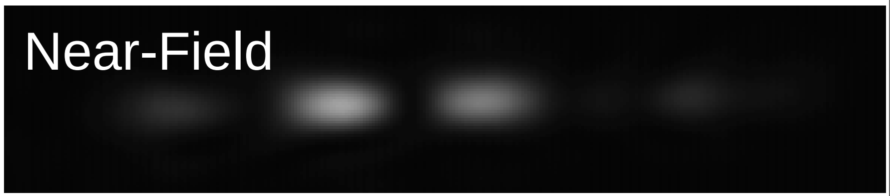


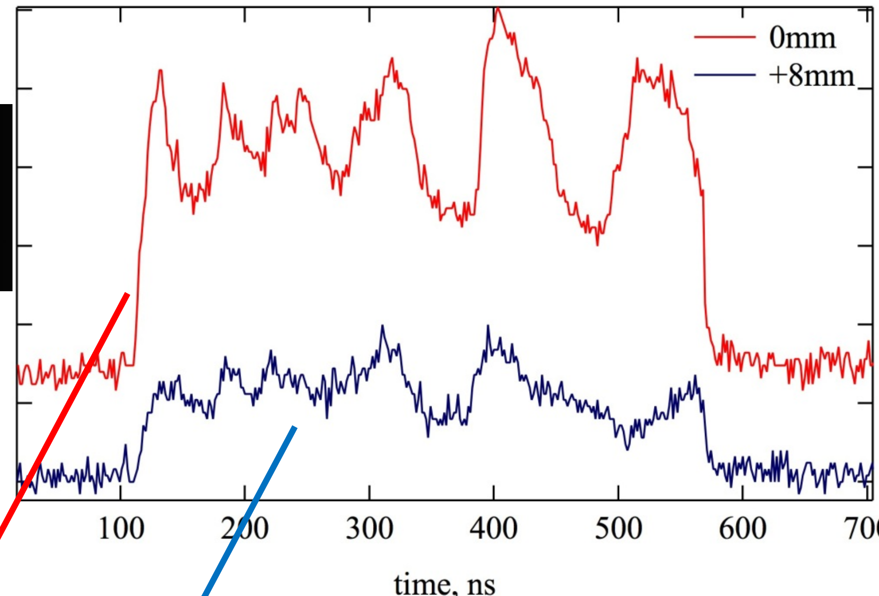
Oscillation interval: ~56ns (17MHz)
17mm cavity length

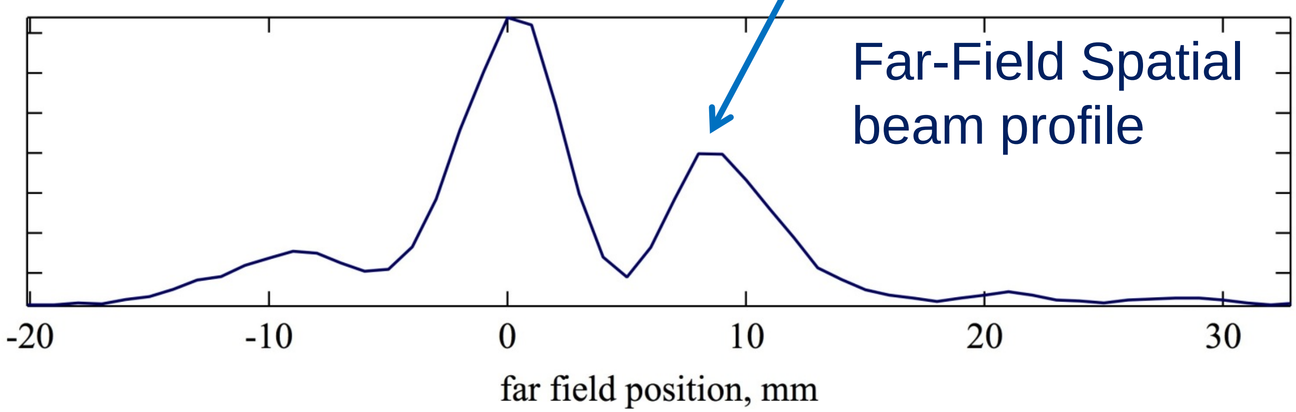


Very Strong Beating

9.6mm cavity
Dual lobes



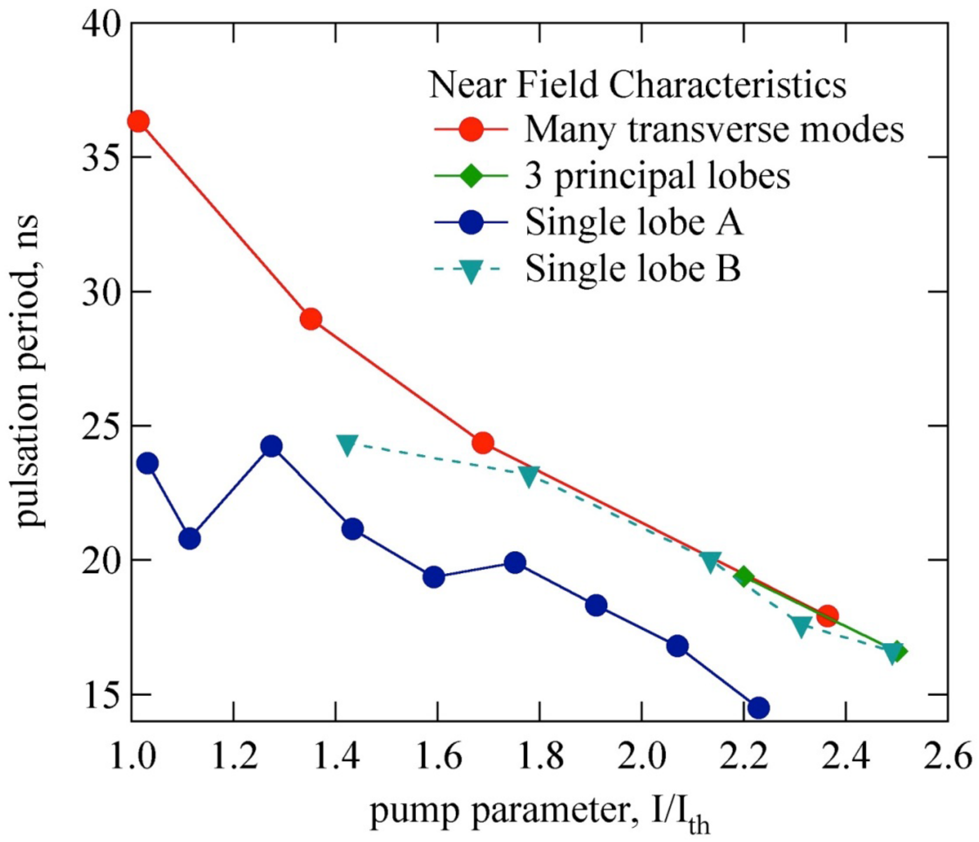




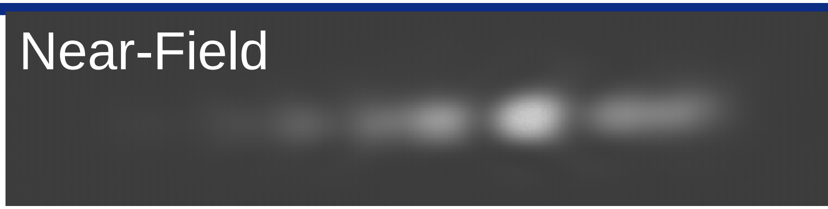
Time Scales

- Oscillations in the Far-Field.
- At I ~ I_{th} *f* ~ 30 to 40MHz.
- High pumping *f*~67MHz.

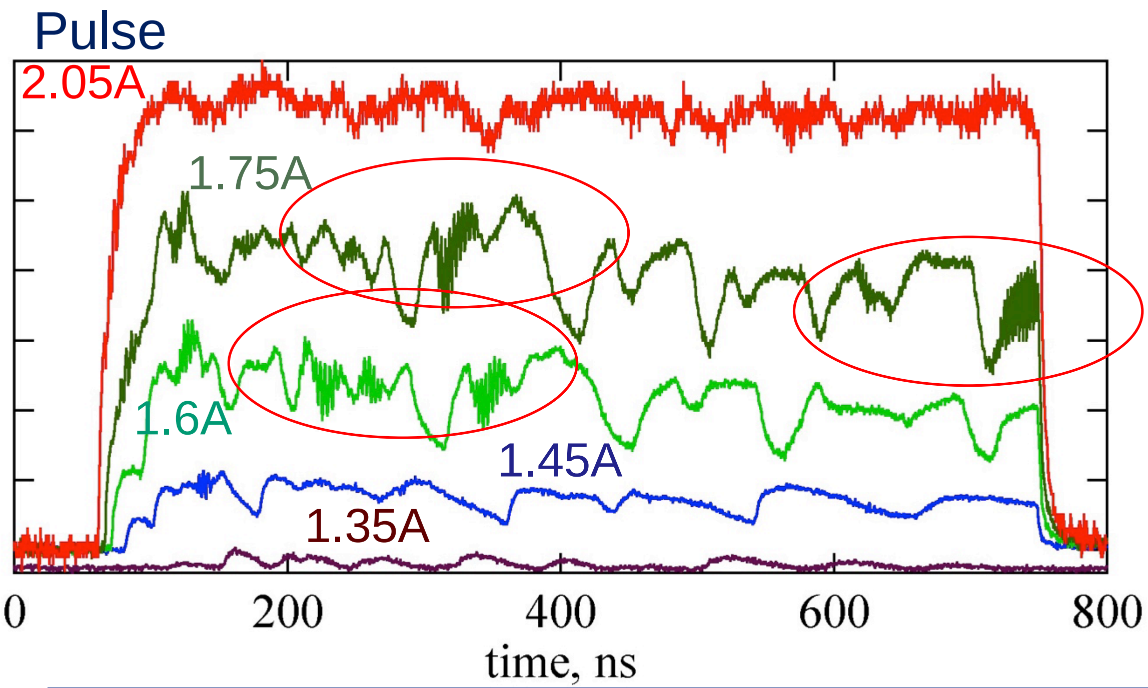
- Doesn’t correspond to relaxation oscillations.
- No clear relationship with an external cavity round-trip oscillation.

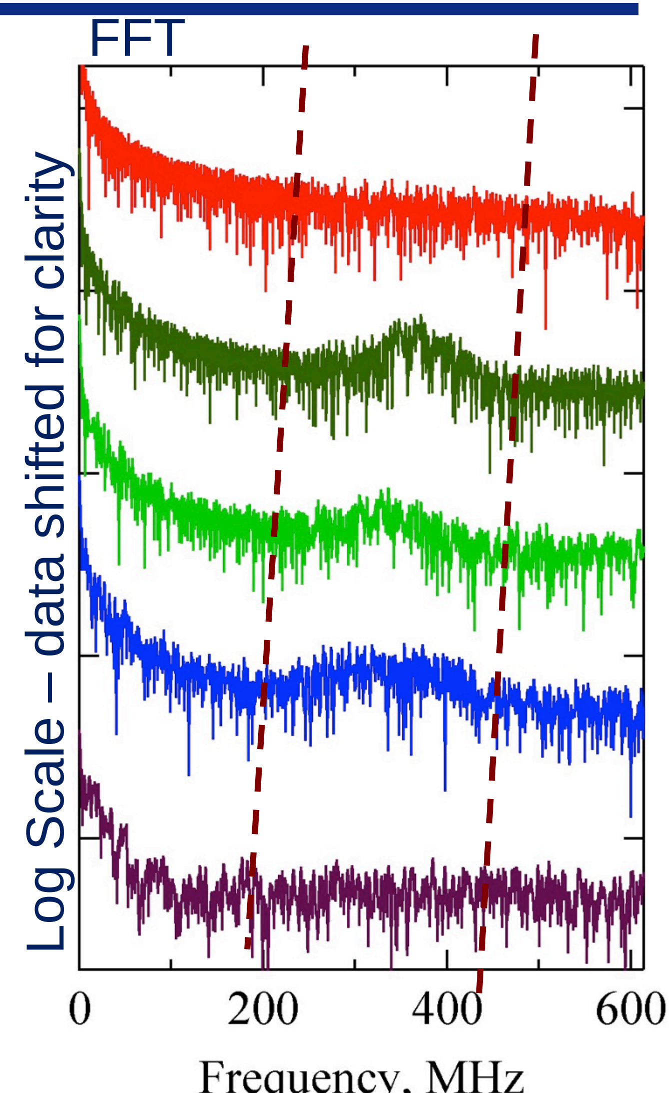


Nonlinear Dynamics

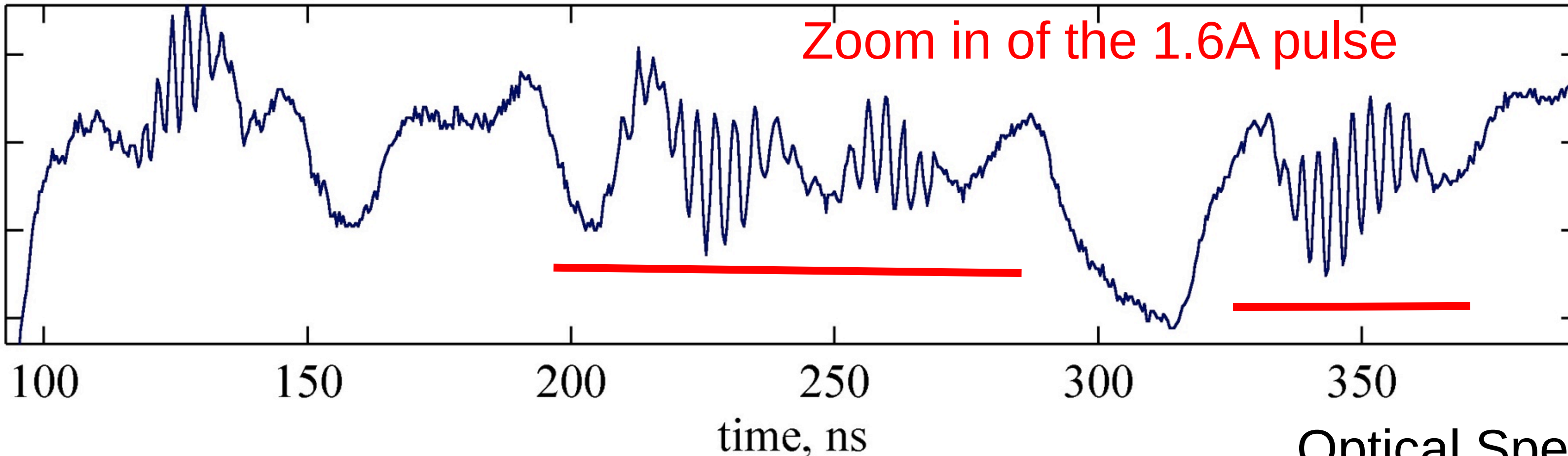


Observe high frequency fluctuations in the time domain and in a Fast Fourier Transform (FFT)

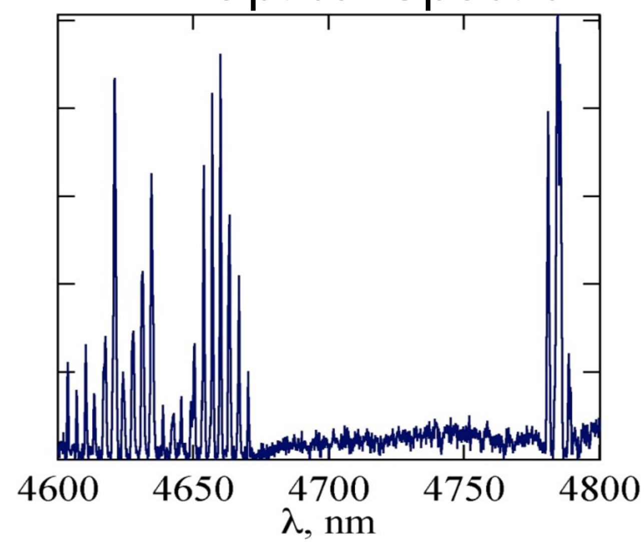




Nonlinear Dynamics



Optical Spectra



- Limited temporal resolution. Oscillations digitized to be 300 to 500MHz
  - **Aliasing of the actual fast oscillations**
- Undamping of an external cavity round-trip oscillation. *f*~4.8GHz
- Probably not chaotic oscillations.
- Alignment is critical to observe these.

Summary I

- BA-QCLs prefer to oscillate in a single transverse mode.
  Partially explained from self-reproduction in the cavity.
- BA-QCLs laser on a number of longitudinal modes.
- With low levels of feedback the mode number stays the same.
  The laser fluence can be concentrated into a few of the antinodes.
- With high levels of feedback other transverse modes can be excited.
- Beam steering in the far-field is easy to achieve.
- Increasing the brightness of the QCL is possible.

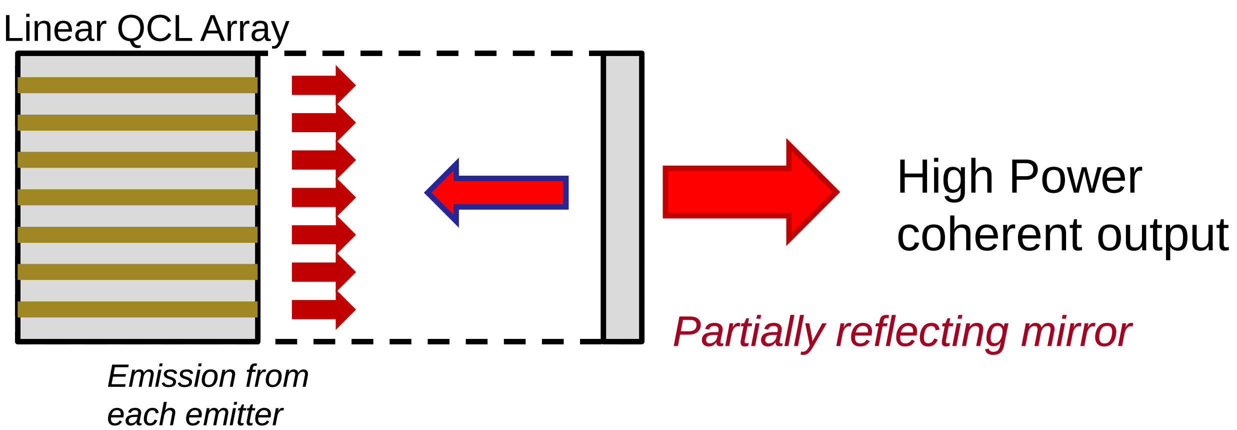
Summary II

- Power switching between longitudinal mode occurs with and without feedback. The time scales are in the 10s of ns.
- Transverse mode switching time scales are on the order of 10s of nanoseconds and pump dependent.
- Transverse mode competition arises from
  - Spatial overlap of the mode with the gain
  - Four-wave mixing couples the transverse modes.
- In the right conditions, the feedback angle of incidence, external cavity oscillations become undamped.
  - The regime to witness these is small.
- The 1ns rise time of the detector limits the ability to resolve the high frequency fluctuations. Aliasing of the digitized signal occurs.

Talbot & Self-Fourier Cavities

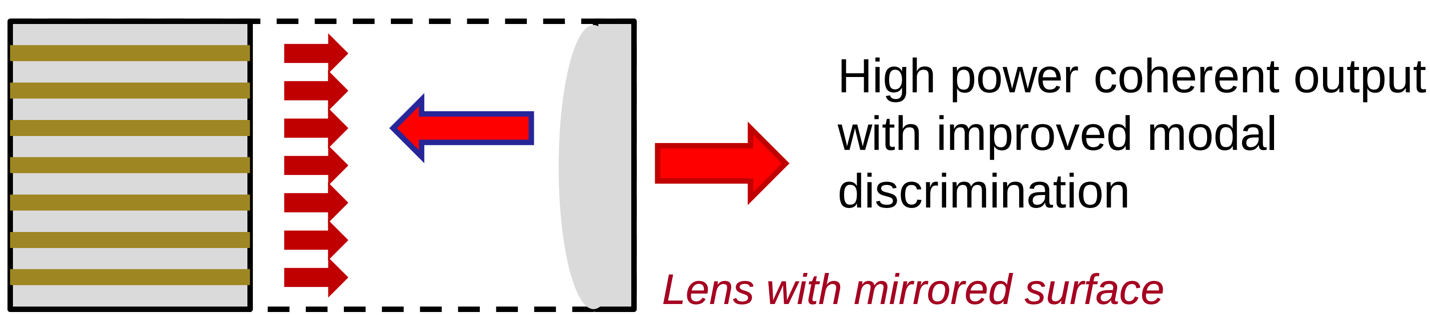
- A linear array of emitters (>3) are phase locked by proper feedback.
- Feedback effects shown above suggest the cavity will be stable in time.

Talbot



Feedback couples into each emitter

Self-
Fourier



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